Building 911C
P.O. Box 5000
Upton, NY 11973-5000
Phone 631 344-4531
Fax 631 344-5954
hershcovitch@bnl.gov

Memo

DATE: *August 30, 2005*

TO: RHIC E-Coolers

FROM: *Ady Hershcovitch*

SUBJECT: **August 30, 2005 Seminar**

David Bruhwiler from Tech-X Corp. in Colorado gave a talk titled “Simulation of dynamical friction with VORPAL --- recent results and status of new code development.” The VORPAL code, though relatively new has had a major impact on the RHIC electron beam cooling at BNL.

Alexei and Vladimir performed a series of experiments at CELSIUS. Among the purposes of the experiments was to measure the cooling force and to compare these experiment results to the Parkhomchuk model as well as the model of Derbenev, Skrinsky and Meshkov. Originally, the Parkhomchuk model had good agreement with experimental that was better than the model of Derbenev, Skrinsky and Meshkov. For both models single particle formulas were used. But after averaging over distribution functions, there was agreement between the models and both agreed with experiments in the range of low relative velocities for which experiments were done.

The VORPAL code has shown good agreement with the models (comparison with experiments have just started), which increased confidence in predicting RHIC E-Cooling by using this code. Last spring Alexei made calculations using the VORPAL code for magnetized cooling. Computations show that the Derbenev, Skrinsky and Meshkov model, without the previously used logarithmic approximation, is in good agreement with VORPAL. And, these new results showed that previous magnetized cooling results underestimated the longitudinal part of the cooling force. In later simulations, Alexei showed that non-magnetized electron beam cooling is feasible as well. Technically, non-magnetized cooling is much easier to achieve.

Below is a copy David Bruhwiler’s talk showing the latest results with VORPAL.

Simulations of Dynamical Friction with VORPAL – recent results & status of new code development

David Bruhwiler,[1]
Alexei Fedotov,[2] Vladimir Litvinenko,[2] Ilan Ben-Zvi[2]
Richard Busby,[1] Dan Abell,[1] George Bell,[1]
Peter Messmer,[1] John Cary[1,3] and Seth Veitzer[1]

1. Tech-X
2. BNL
3. U. Colorado

C-AD Accelerator Physics Seminar
BNL
August 30, 2005

Tech-X Corporation
5621 Arapahoe Ave., Suite A
Boulder, Colorado 80303
http://www.txcorp.com

Work supported by US DOE, Office of NP, SBIR program, contract # **DE-FG03-01ER83313**

Outline

- Funding & near-term priorities
- Effect of solenoidal magnetic field errors
- Wiggler concept for unmagnetized cooling
- Reduced model for binary collisions
- Simulating the friction due to "dielectric response"

Funding & Near-term Priorities

- New Phase II SBIR grant from DOE/NP
  - July, 2005 through June, 2007; ~ 4 FTE
  - D. Bruhwiler, R. Busby, D. Abell, G. Bell
- Near-term priorities
  - Speed-up the simulations
    - New approach to parallelization of binary collision algorithm
    - Reduced model for binary collisions
  - Simulate the unmagnetized cooling concept
    - in particular, what is the effect of a wiggler field?
  - Simulate the effects of solenoidal field errors

Motivation for Study of Magnetic Field Errors

- The effect of magnetic field errors in a solenoid on the dynamical velocity drag (i.e. friction) of an ion in an electron cooler is not well understood
  - The parametric model of Parkhomchuk treats field errors as an effective transverse rms velocity of the electron Larmor circles
    - Contribution appears in same place as $V_{e,rms,||}$
    - In the absence of an explicit model, field errors have been treated as an effective increase in $V_{e,rms,||}$
- Our primary interest is the cooler for RHIC II
  - We consider the CELSIUS ring here, to take advantage of recent experiments
  - We consider two very different models for the errors

Magnetic field errors – "Model 1"

- A sum of sinusoidal terms (lab frame)

$$B_x = \sum_i b_i \frac{k_{x,i}}{k_{z,i}} \exp\left(k_{x,i} x\right) \exp\left(k_{y,i} y\right) \sin\left(k_{z,i} z + \varphi_{z,i}\right)$$

$$B_y = \sum_i b_i \frac{k_{y,i}}{k_{z,i}} \exp\left(k_{x,i} x\right) \exp\left(k_{y,i} y\right) \sin\left(k_{z,i} z + \varphi_{z,i}\right)$$

$$B_z = B_0 + \sum_i b_i \exp\left(k_{x,i} x\right) \exp\left(k_{y,i} y\right) \cos\left(k_{z,i} z + \varphi_{z,i}\right)$$

$$k_{z,i}^2 = k_{x,i}^2 + k_{y,i}^2 \qquad \lambda_i = 2\pi / k_{z,i}$$

  - a more general form of the equations is allowed
  - we assume $b_i \ll B_0$ for all i
  - appropriate choices for b_i, λ_i, etc. are not yet clear
  - here, we consider a single component

Magnetic field errors – "Model 2"

- A sum of piece-wise constant "tilts" (lab frame)

$$B_x = \sum_i b_{x,i} H\left(z - z_{x,i}\right) H\left(z_{x,i+1} - z\right)$$

$$B_y = \sum_i b_{y,i} H\left(z - z_{y,i}\right) H\left(z_{y,i+1} - z\right)$$

$$B_z = B_0$$

  - *H(x)* is the unit Heaviside function
  - we assume $b_{ix}, b_{iy} << B_0$ for all *i*
  - small abuse of Maxwell's eqn.'s at discontinuities
  - parameters taken from design report
    - M. Sedlacek et al., "Design and Construction of the CELSIUS Electron Cooler," http://preprints.cern.ch/cgi-bin/setlink?base=cernrep&categ=Yellow_Report&id=94-03
    - amplitude of tilts (highly variable) is ~1.e-03
    - length of segments (highly variable) is ~20 cm

Fields are Lorentz-transformed to beam frame

- VORPAL cooling sim.'s are in the beam frame
  - C. Nieter and J.R. Cary, J. Comp. Phys. 196, 448 (2004).

$$B_z' = B_z\left(x', y', \gamma\beta ct'\right)$$

$$B_x' = \gamma B_x\left(x', y', \gamma\beta ct'\right) \quad B_y' = \gamma B_y\left(x', y', \gamma\beta ct'\right)$$

$$E_x' = -\beta c B_y' \qquad E_y' = \beta c B_x' \qquad E_z' = 0$$

- **E** fields are dominant for "relativistic" coolers
  - because electrons are non-relativistic in the beam frame
  - only partially true for CELSIUS, for which β~0.3

Basic Parameter set with 6 variations

Symbol	Meaning	Value	Units
B_0	solenoid field	0.1	T
L_{sol}	solenoid length	2.5	m
β	proton bunch velocity / c	0.308	
τ_{lab}	interaction time (lab frame)	$2.7\text{x}10^{-8}$	s
τ_{beam}	interact. time (beam frame)	$2.6\text{x}10^{-8}$	s
Δt	largest time step	$2.6\text{x}10^{-12}$	s
dt_{min}	smallest time step	$8.0\text{x}10^{-14}$	s
ω_{pe}	e- plasma frequency	$4.1\text{x}10^{8}$	rad/s
Ω_L	e- Larmor frequency	$1.8\text{x}10^{10}$	rad/s
r_L	e- Larmor (gyro-) radius	$7.9\text{x}10^{-6}$	m
$L_{x,y,z}$	sim. domain dimensions	$6.0\text{x}10^{-4}$	m
n_e	e- number density	$5.4\text{x}10^{13}$	m^{-3}
N_e	# of simulated e-'s	$1.2\text{x}10^{3}$	
$\Delta_{e,\perp}$	transverse rms e- velocity	$1.4\text{x}10^{5}$	m/s
$\Delta_{e,\|}$	long. rms e- velocity	$3.0\text{x}10^{3}$	m/s
$\Delta_{eff,\|}$	effective long. rms e- vel.	$9.0\text{x}10^{3}$	m/s

We consider 6 separate cases –

2 with field errors & 4 without

"ice" – $\Delta_{e,\|}$ = 0 (no errors)

"cld" – $\Delta_{e,\|}$ = 3000 (no errors)

"wrm"– $\Delta_{e,\|}$ = 9000 (no errors)

"hot" – $\Delta_{e,\|}$ =18000 (no errors)

"sin" – $\Delta_{e,\|}$ = 3000 (Model 1)

"err" – $\Delta_{e,\|}$ = 3000 (Model 2)

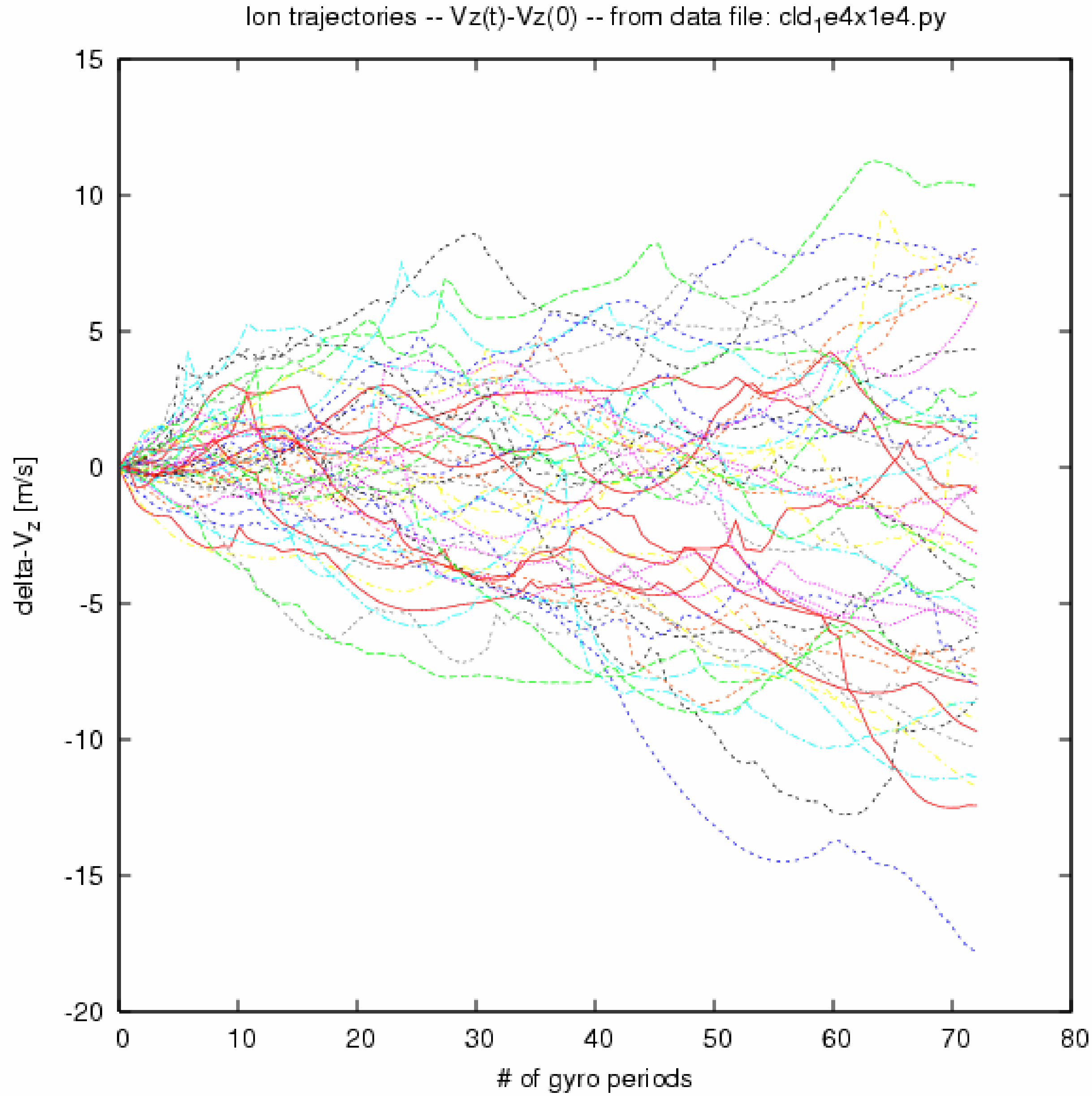
Diffusive dynamics can obscure friction/drag

- For a single pass through the cooler
  - Diffusive velocity kicks are larger than velocity drag
  - Consistent with theory
- For sufficiently large $\Delta_{e,||}$
  - numerical trick of e-/e+ pairs can suppress diffusion [2]
  - not valid for CELSIUS parameters
- Only remaining tactic is to generate 100's of trajectories
  - Central Limit Theorem states that mean velocity drag is drawn from a Gaussian distribution, with rms reduced by $N_{traj}^{1/2}$ as compared to the rms spread of the original distribution
  - Hence, error bars are +/- 3 rms / $N_{traj}^{1/2}$
- Not practical to routinely generate 100's or 1000's of trajectories by hand, one at a time
  - run 8 trajectories simultaneously
  - use "task farming" approach to automate many runs

TaskDLsh – Task Farming Parameter Scans

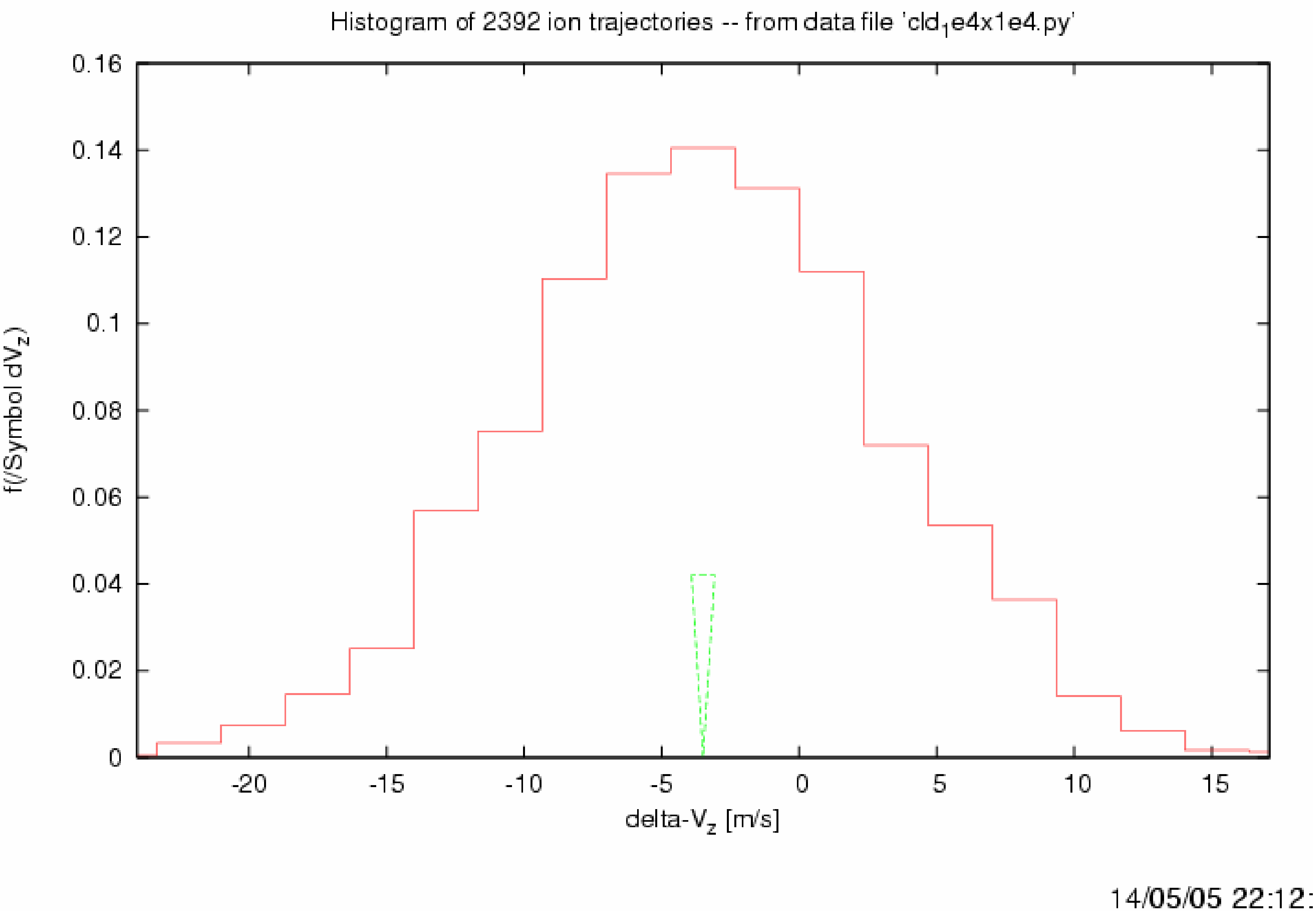
- Distributed workers are launched according to cluster scheduling software, which look for tasks to process
  - shell scripts which launch simulations with different parameters
- A "tuple space" of independent tasks (different parameters) is made available to all processors
- Processors choose and independently execute tasks based on their resources
- Provides efficient scheduling, load balancing, and fault tolerance
  - TaskDL: http://www.txcorp.com/products/FastDL/taskdl/

“cld” parameters – $\Delta_{rms,||}$ = 3000 (no field errors)

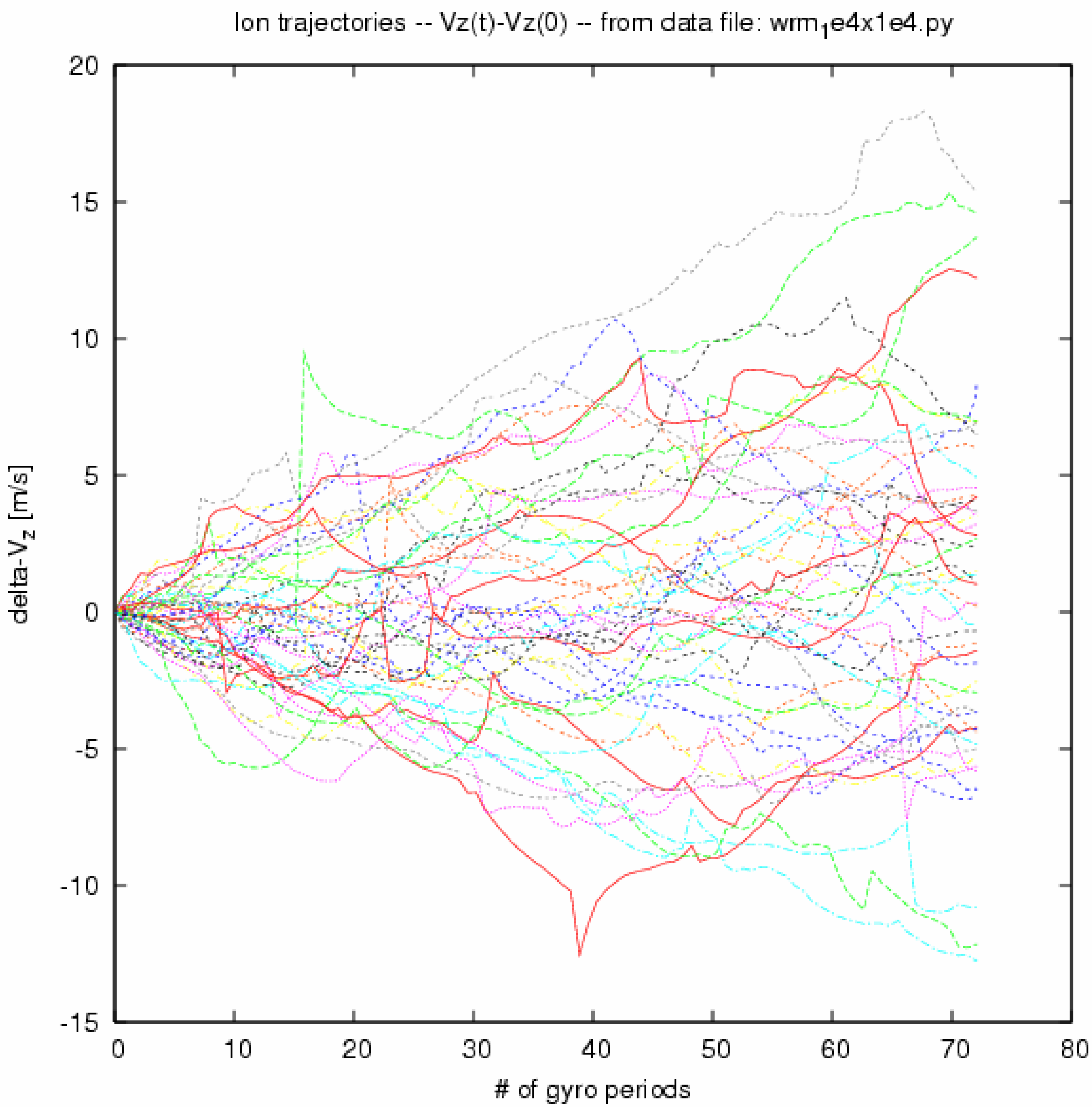


14/05/05 22:12:37

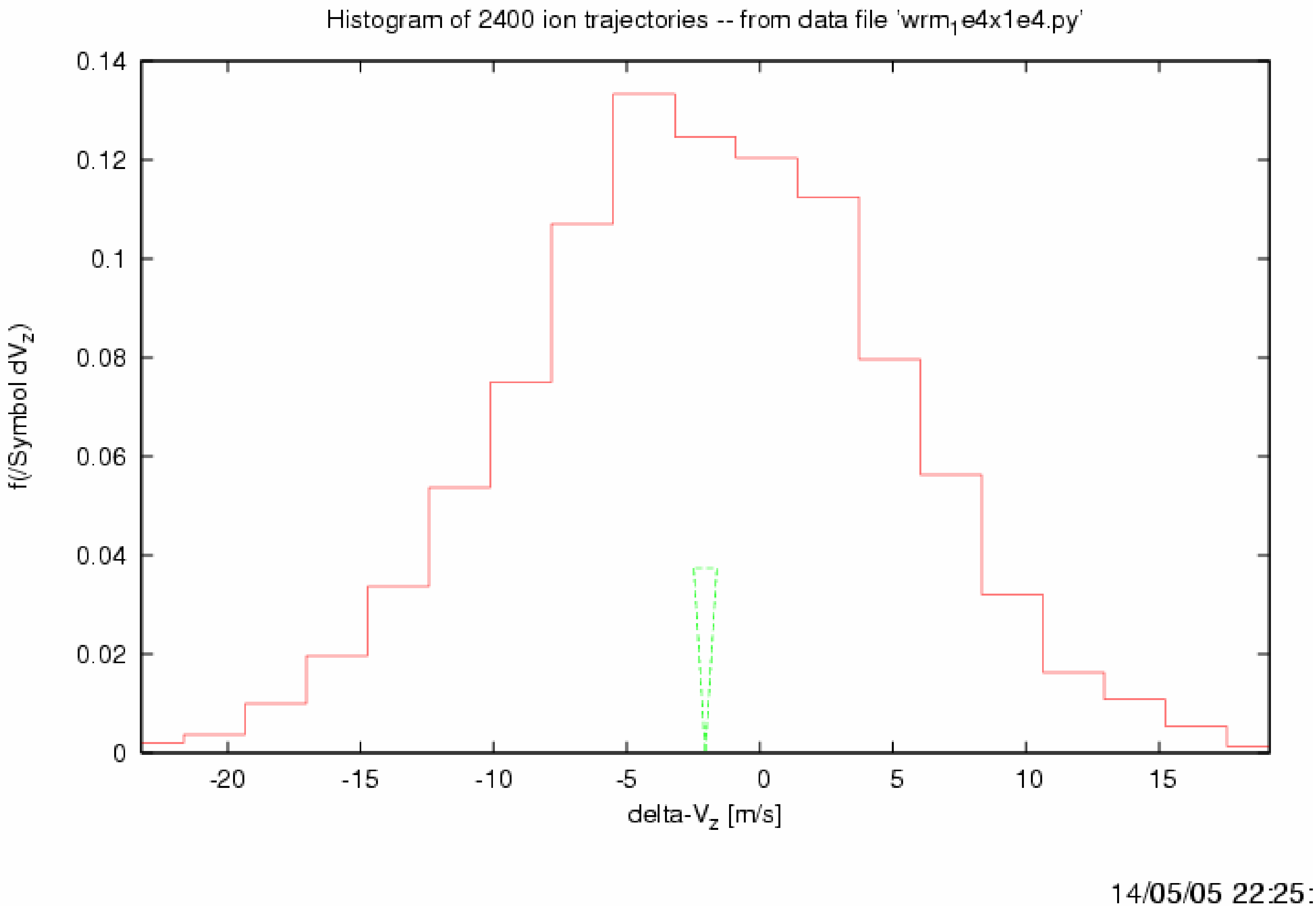
“cld” parameters – $\Delta_{rms,||}$ = 3000 (no field errors)



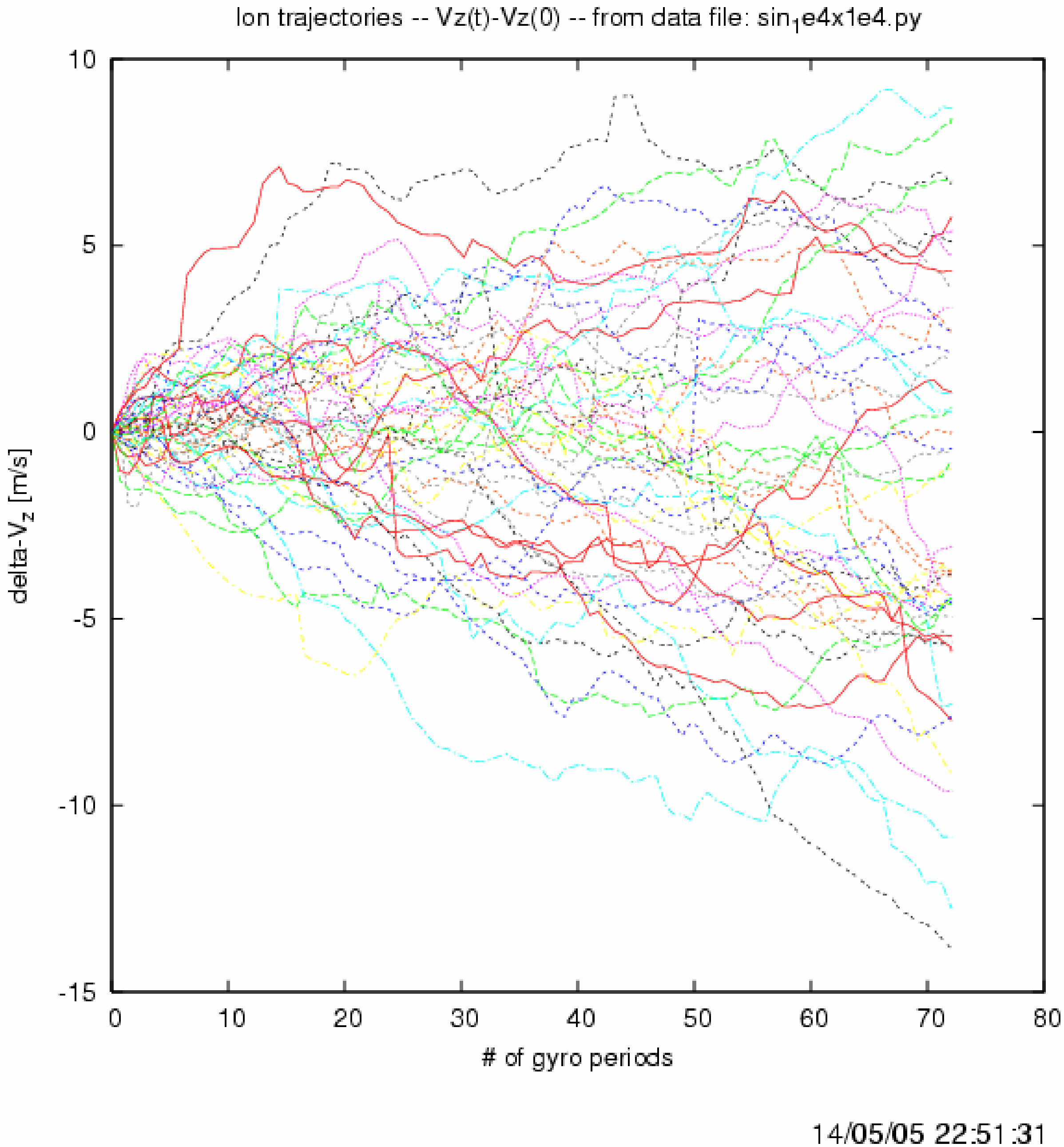
“wrm” parameters – $\Delta_{rms,||}$ = 9000 (no field errors)



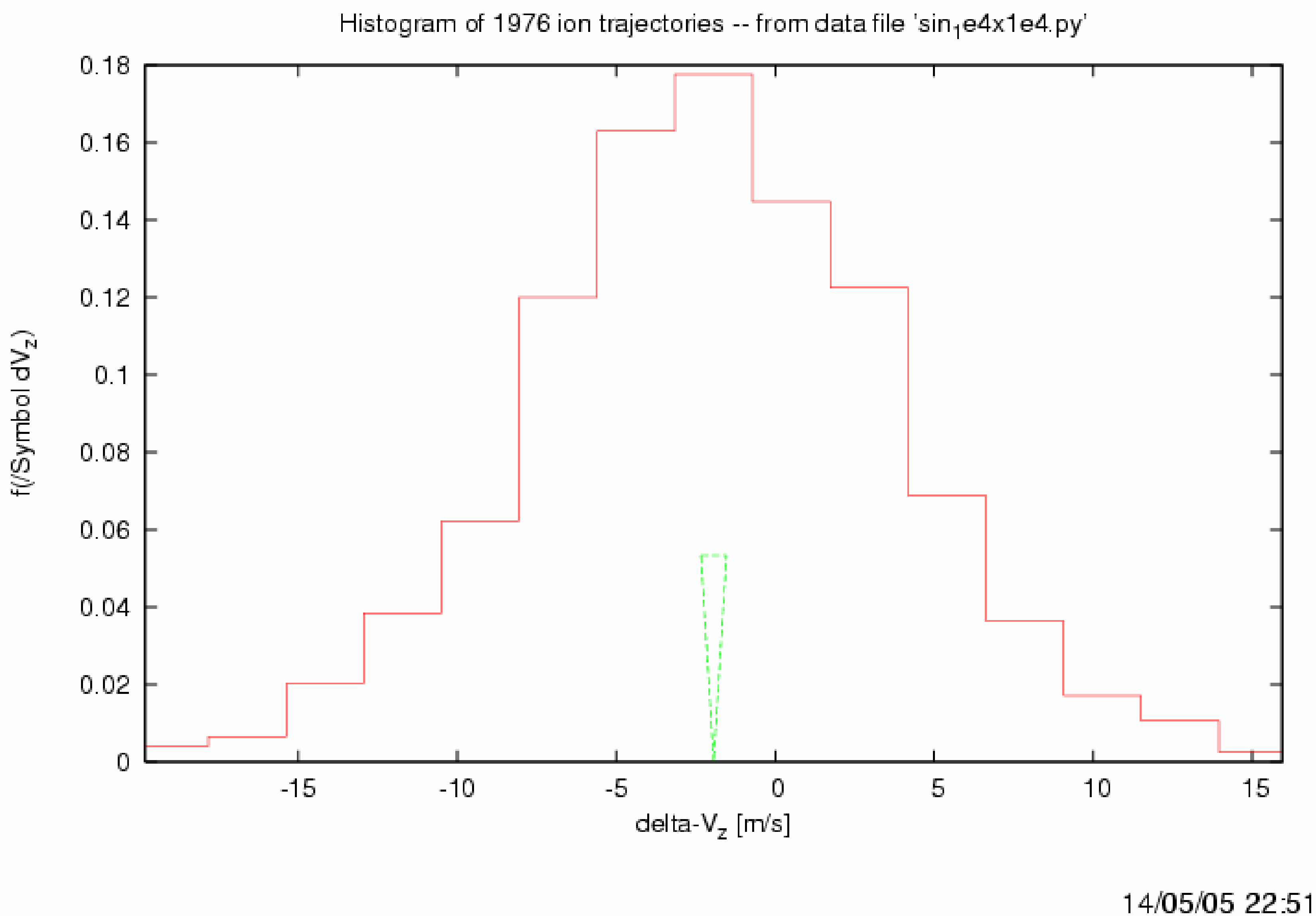
“wrm” parameters – $\Delta_{rms,||}$ = 9000 (no field errors)



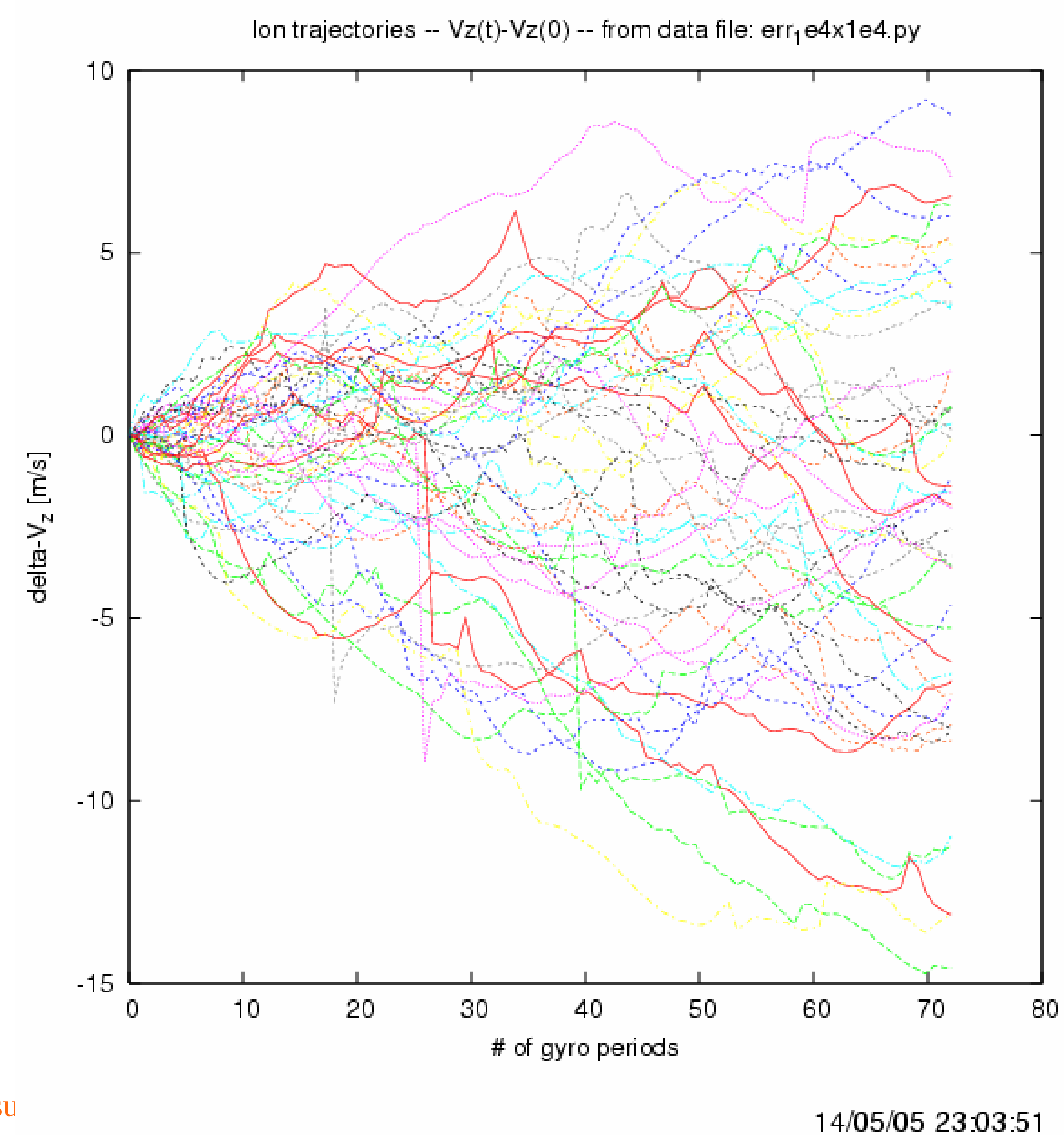
"sin" parameters – $\Delta_{rms,||}$ = 3000 (Model 1)



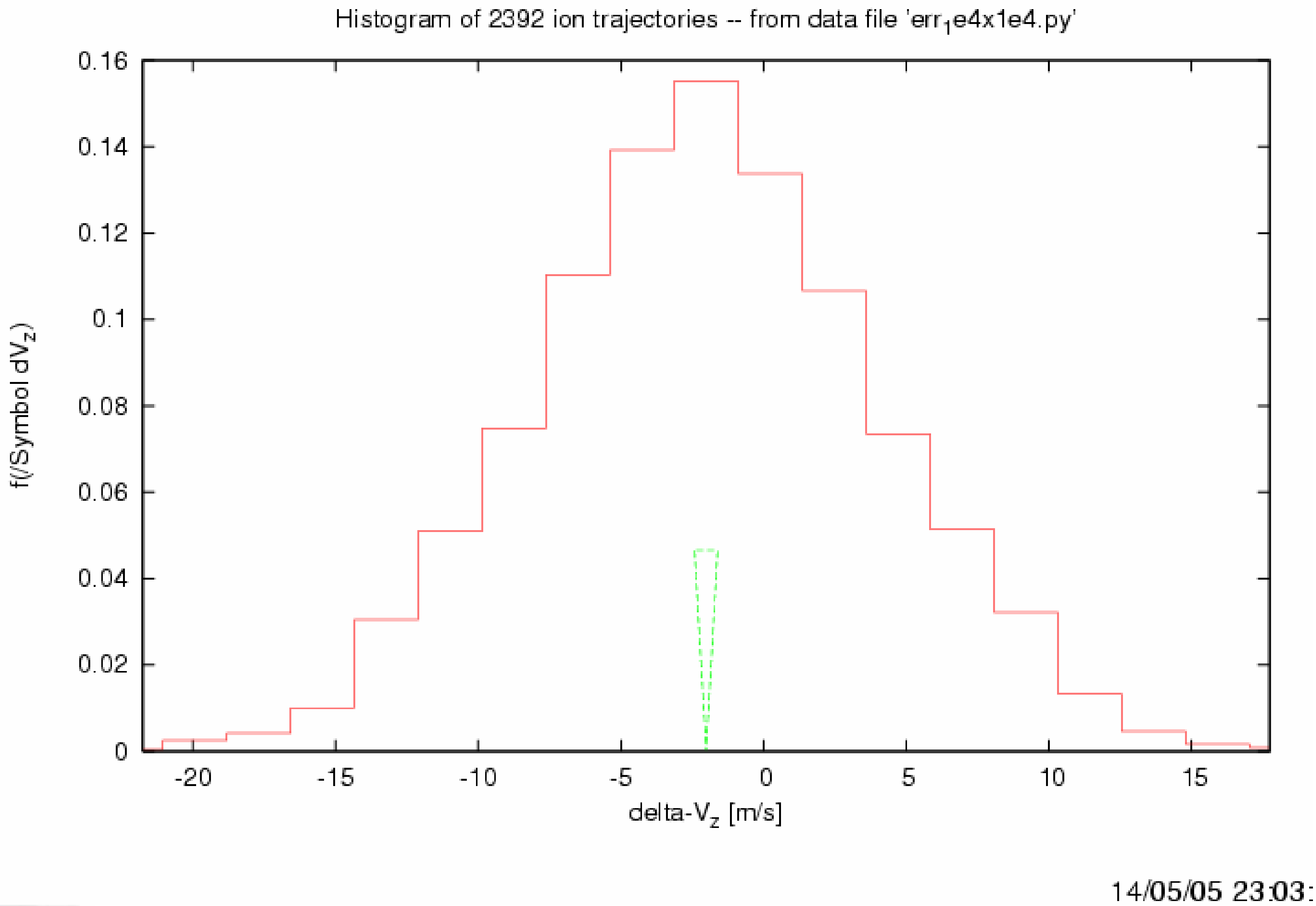
"sin" parameters – $\Delta_{rms,||}$ = 3000 (Model 1)



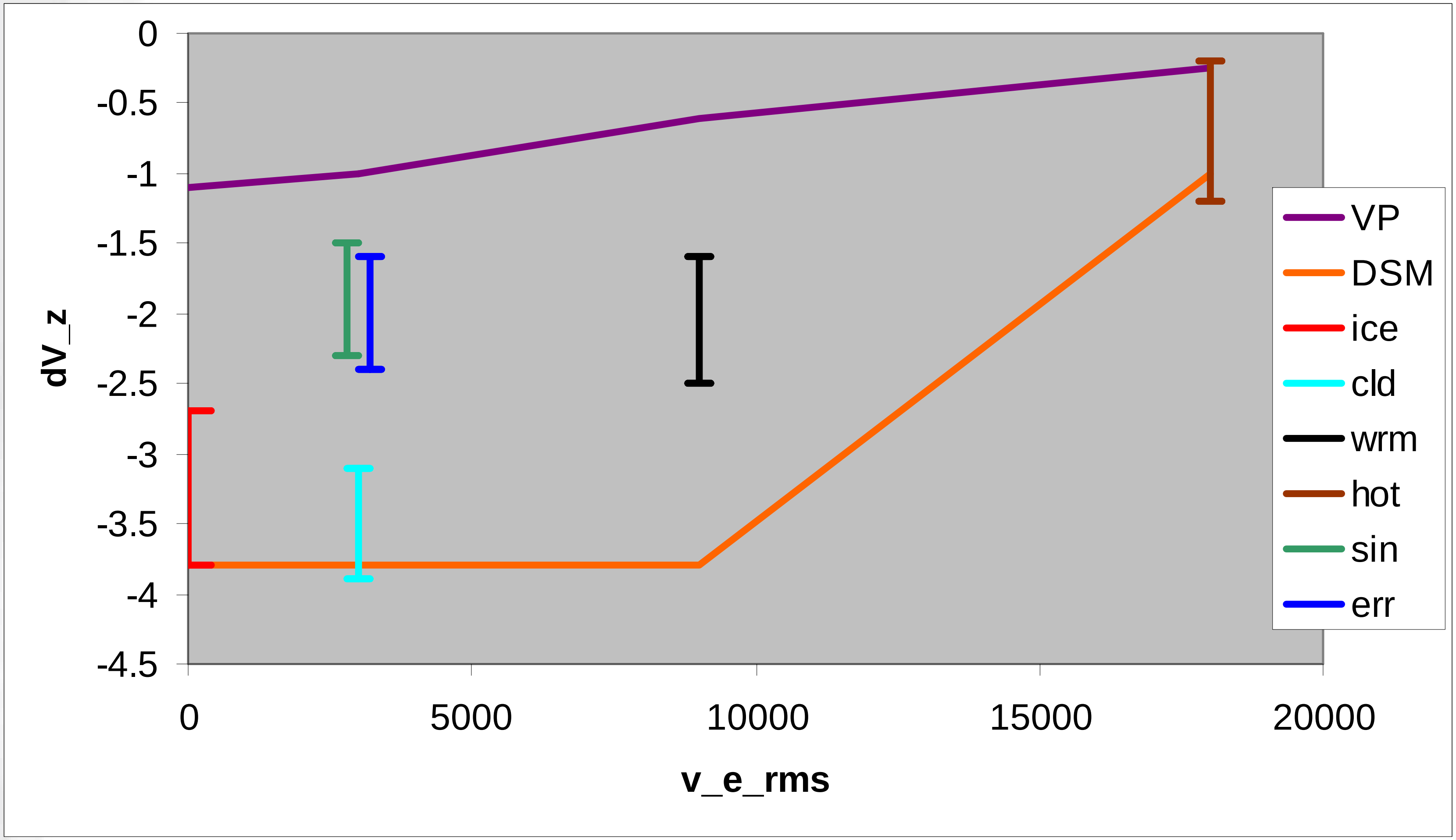
“err” parameters – $\Delta_{rms,||}$ = 3000 (Model 2)



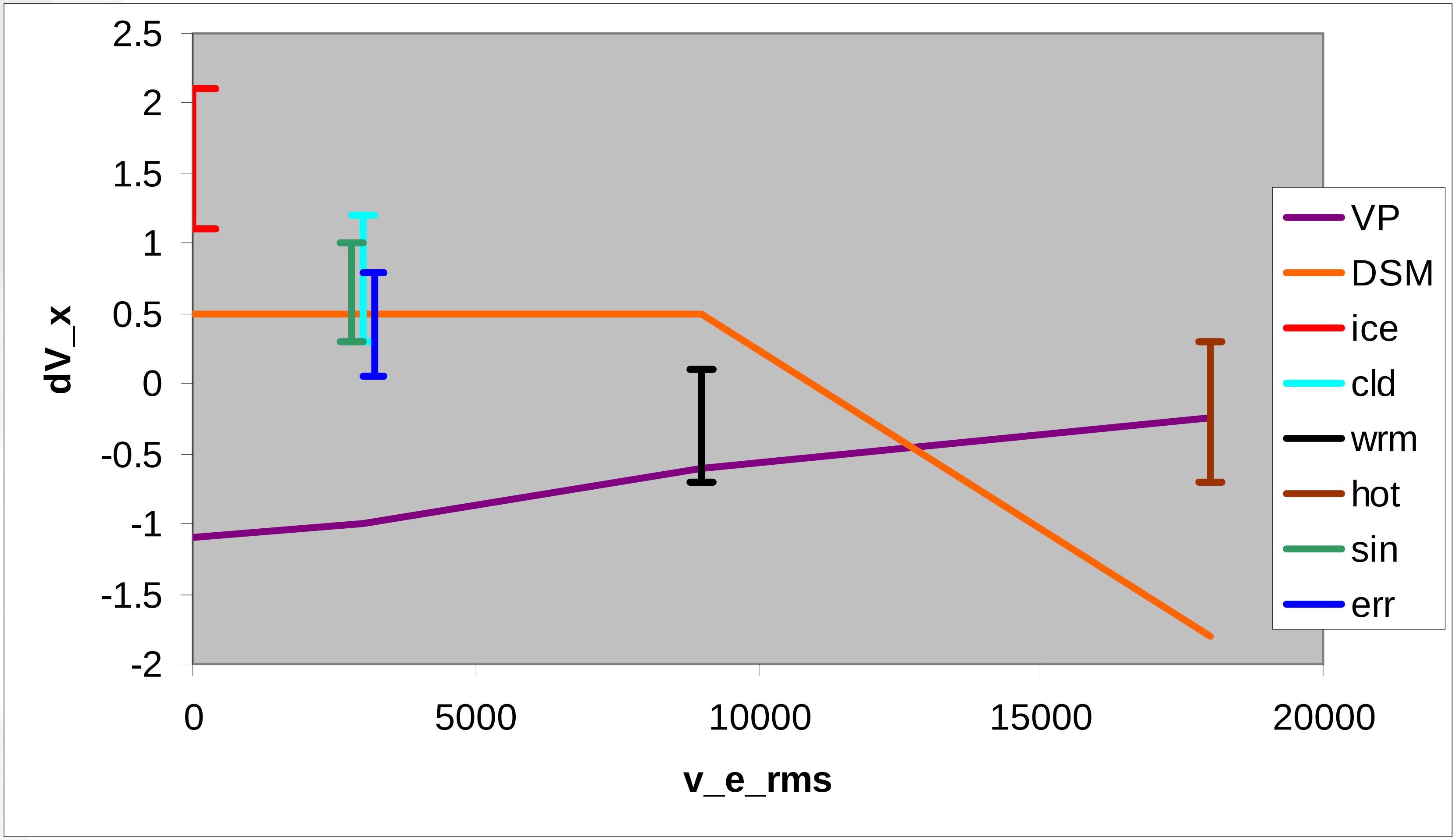
“err” parameters – $\Delta_{rms,||}$ = 3000 (Model 2)



Effect of $\Delta_{rms,||}$ on δV_z



Effect of $\Delta_{rms,||}$ on δV_x



Tentative Conclusions regarding Field Errors

- Field errors reduce friction in magnetized coolers
- Two models were tested
  - a single sinusoidal component
  - a series of piece-wise constant “tilts”
- Both models show very similar effects
  - longitudinal velocity drag is significantly reduced
    - in agreement with parametric increase of $\Delta_{rms,||}$
  - transverse velocity drag is less affected
    - NOT consistent with parametric increase of $\Delta_{rms,||}$
- Powerful use of VORPAL friction simulations
  - no other way to obtain these results

Future Work – wiggler approach to RHIC cooler

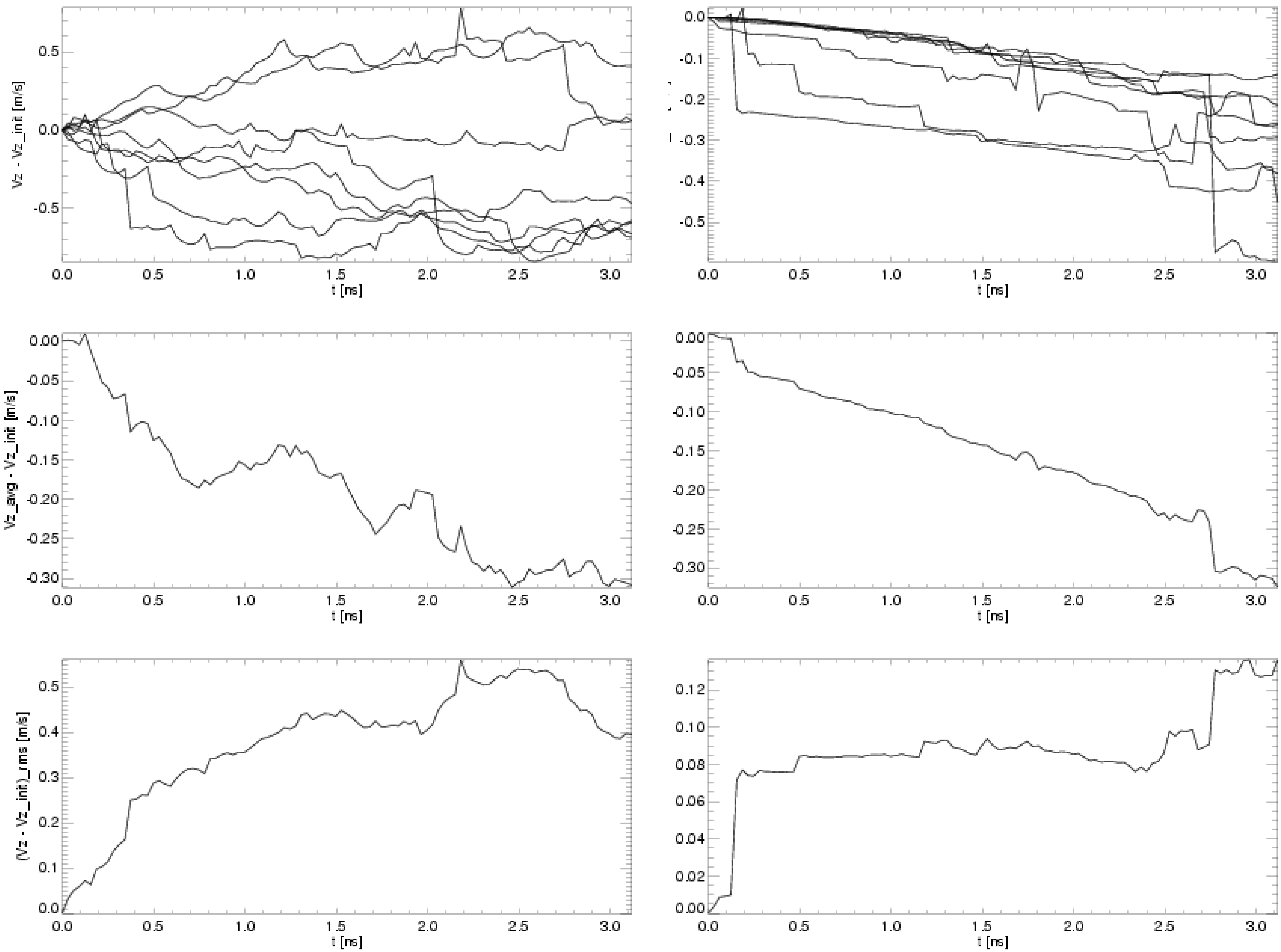
- The Accelerator Physics Group of the RHIC Electron Cooling Project has developed the concept of a "wiggler-based approach" to electron cooling for RHIC II.

- The baseline design remains a more traditional solenoid-based cooler concept.

Wiggler approach to RHIC cooler – Motivation

- Why look for alternatives to solenoid design?
  - solenoid design is challenging; expensive construction
    - L~13 m; B~2-5 T; relative field errors~1.e-05
  - electron bunch parameters are extremely demanding
    - 20 nC, with reasonable emittance and high rep rate
    - e-'s must be magnetized at photocathode
      - high-charge SC e- gun with magnetic field?
      - retain magnetization through accelerator/transport/self-fields?
- What are the advantages of a wiggler?
  - long (~50 m) conventional wigglers are not difficult
  - magnetic fields are modest (~10 Gauss)
    - focus e- beam and reduce recombination rate
    - increase minimum impact parameter of Coulomb logarithm
  - e- bunch is easier: ~2 nC and un-magnetized

Unmagnetized simulations for “wiggler” param.’s



Wiggler approach – initial VORPAL simulations

- Tests in absence of wiggler field look promising
  - unmagnetized dynamical friction agrees with theory
  - numerical e-/e+ trick suppresses diffusion by 4x
    - D. Bruhwiler et al., Proc. 33rd ICFA Beam Dynamics Workshop (2004)
- Magnetic field has following form (lab frame)

$$B_x = B_0 \cos(2\pi\, z / z_0)$$

$$B_y = B_0 \sin(2\pi\, z / z_0)$$

$$B_z = B_0 \frac{2\pi\, y}{z_0} \cos(2\pi\, z / z_0) - B_0 \frac{2\pi\, x}{z_0} \sin(2\pi\, z / z_0)$$

  - circularly-polarized EM wave in the beam-frame
  - simulations with this field haven't yet started

Motivation for semi-analytic Reduced Model

- VORPAL simulations of e- cooling have been *intriguing* and *tantalizing* and even *important*
  - but we need more simulation results faster
- Friction force is dominated by 2-body collisions
- Reduced model treats each ion/e- pair separately
  - Orbital dynamics treats such interactions analytically
  - Time step is set by gyro-period or other physics
  - This approach should be orders of magnitude faster

Overview of reduced model for binary collisions

- Ion dynamics is of primary interest
  - ions are much more massive than electrons
  - ion motion is very weakly perturbed by collisions
- Use analytical two-body theory; a single ion
  - handle each e- separately in center-of-mass frame
  - calculate initial orbit parameters in relevant plane
  - advance dynamics for a fixed time step
    - electron's new position and velocity are known
    - changes to ion position/velocity are small perturbations
  - total ion shift is sum of individual changes
- Add external **E**, **B** fields via operator splitting
  - J. Boris, Proc. Conf. Num. Sim. Plasmas, (1970), p. 3.
- Benchmark w/ tested binary collisions in VORPAL

Reduced Model – some orbit theory details

- Must find the plane in which partial orbit occurs
  - necessary rotations (yaw, pitch, roll) are complete
  - transformations are messy, but straightforward
  - “initial” positions & velocities obtained in this plane
- Then standard orbital parameters are calculated

$$\frac{\alpha}{r} = 1 + \varepsilon \cos\theta \qquad \alpha = \frac{l^2 4\pi\varepsilon_0}{m_e Z e^2} \qquad \varepsilon = \sqrt{1 + \frac{2El^2 (4\pi\varepsilon_0)^2}{m_e (Ze^2)^2}}$$

- For hyperbolic (or elliptical motion):
  - one can obtain *t* as an explicit function of θ
  - this must be inverted numerically

Motivation for “Dielectric Response” Simulations

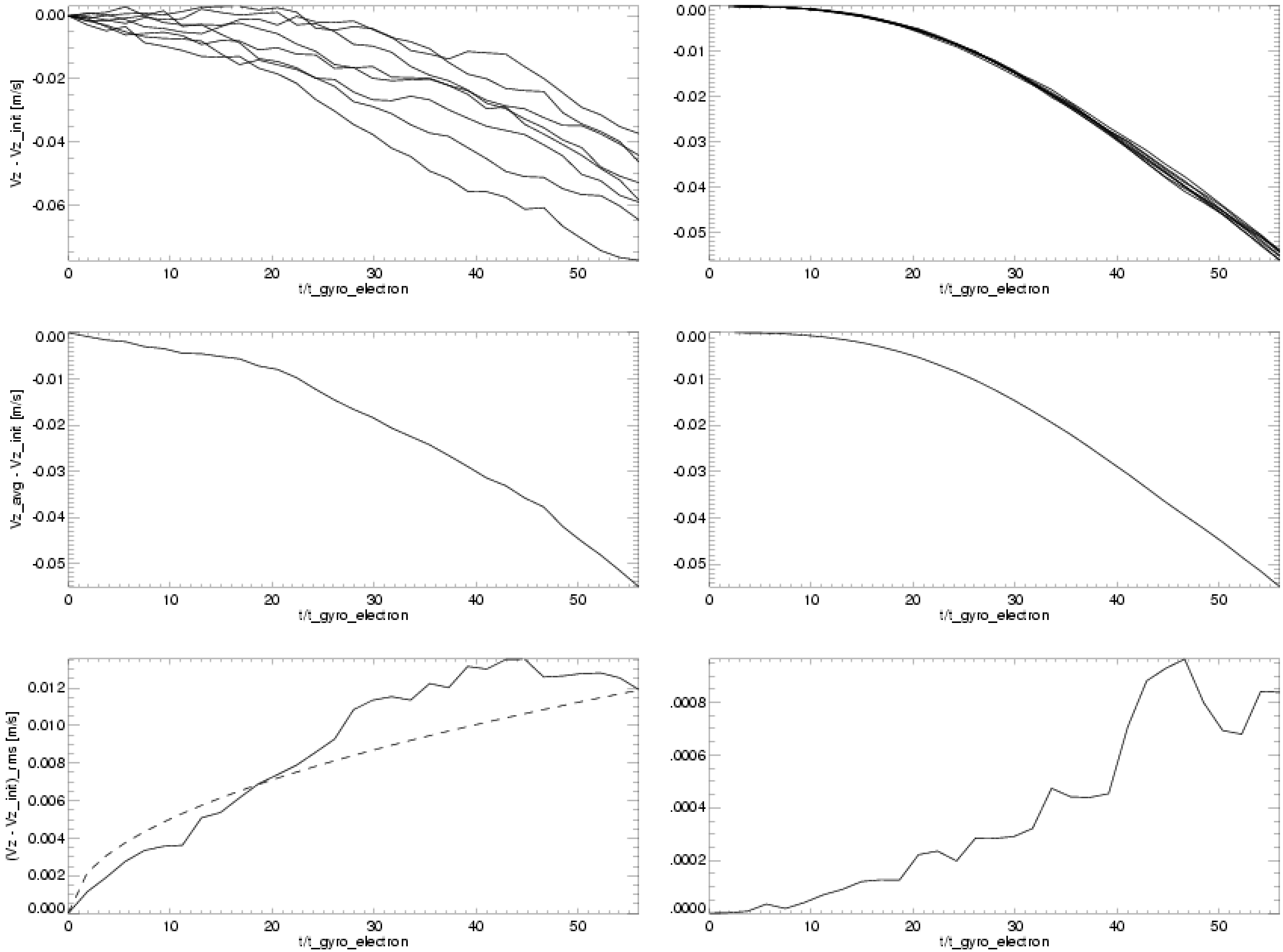
- Zwicknagel et al. have shown that one can simulate the “dielectric response” of a plasma
  - M. Walter, C. Toepffer, G. Zwicknagel, Nuclear Inst. & Methods in Physics Research B **168** (2000) pp. 347-361.
  - use electrostatic PIC (particle-in-cell)
  - reduce noise by using many (~100) electron macro-particles for each physical e-
- This approach very different from binary collisions
- VORPAL can simulate electrostatic PIC
  - P. Messmer and D. Bruhwiler, “A parallel electrostatic solver for the VORPAL code,” Comp. Phys. Comm. **164** (2004), p. 118.
  - uses “Aztec” solver from Sandia National Lab
  - scales well to hundreds of processors on IBM SP
- Could combine reduced model binary collisions between e-/ion with electrostatic PIC for e-/e-

Some initial PIC simulations w/ RHIC param.'s

Parameter:	Description	Value
n_e	Electron density	2.0e+15 e^-/m^3
B	Constant magnetic field in z	5.0 Tesla
Ω	Gyrofrequency = $q_e B / m_e$	8.793e+11 rad/sec
υ	Gyroperiod = $2\pi / \Omega$	7.146e-12 sec
r_e	Gyroradius = v_e / Ω	9.098e-06 m
τ	Ending time of integration	4.0e-10 sec
N_g	Number of gyroperiods	55.975
Ve_rms_x	Electron velocity rms (x & y)	8.0e+06 m/s
Ve_rms_z	Electron velocity rms (z)	1.0e+05 m/s
Z_ion	Charge of the gold ion, in units of q_e	79

- The rms spread of traj.'s in these simulations is dominated by standard PIC noise on the grid
  - i.e. it is not physical diffusion due to binary collisions
- Correlated e-/e+ pairs strongly reduce the noise
- More work is required to make sure the obtained results are physically valid
  - The runs are numerically intensive; typically parallel

Dielectric response sim.'s w/ e-'s (left) & e-/e+ pairs



Acknowledgements

We thank A. Burov, P. Schoessow, P. Stoltz, V. Yakimenko & the Accelerator Physics Group of the RHIC Electron Cooling Project for many helpful discussions. Discussions with A.K. Jain regarding solenoid field errors were especially helpful.

Work at Tech-X Corp. was supported by the U.S. Dept. of Energy under grants DE-FG03-01ER83313 and DE-FG02-04ER84094. We used resources of NERSC.